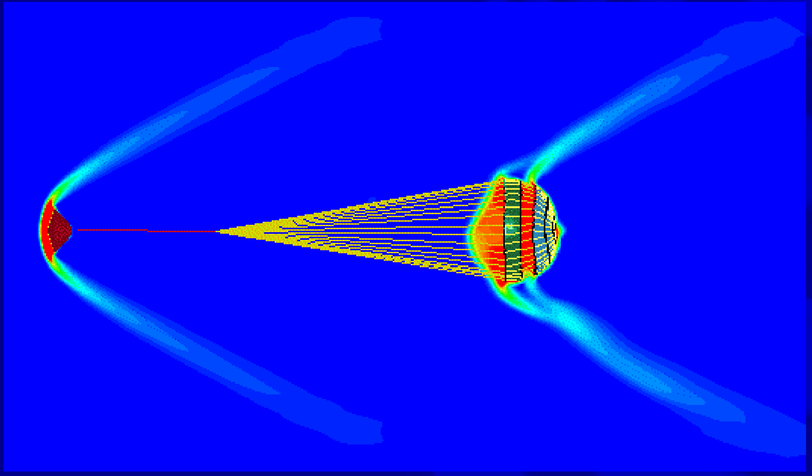
Short Course on Controlled Entry and Descent into Planetary Atmospheres

Descent



Steve Lingard

steve.lingard@vorticity-systems.com

Vorticity Ltd

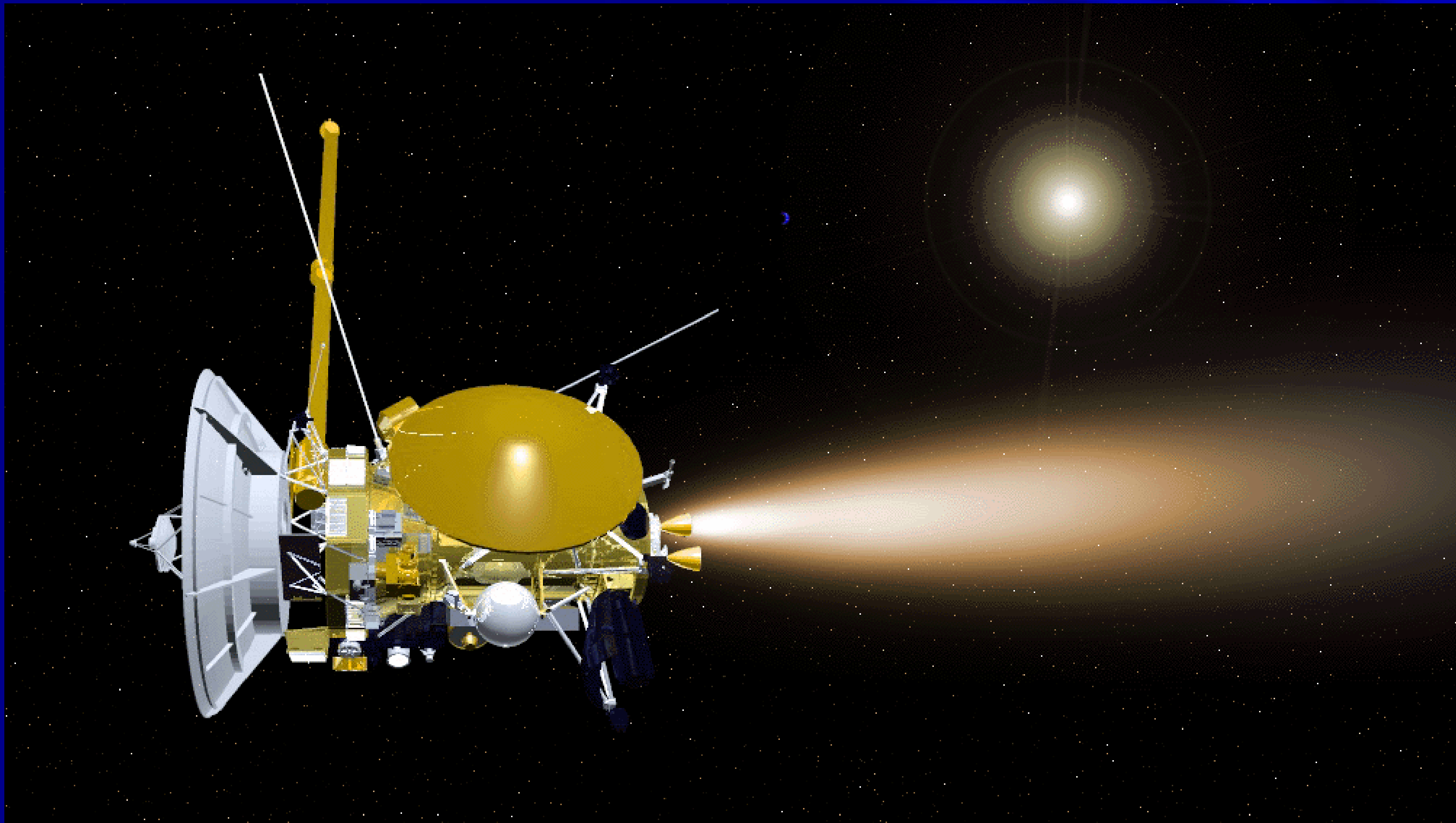
Oxfordshire, UK

Parachutes for Space Use

- Parachutes have been closely linked to many space missions.
- Many vehicles launched into space have had parachutes on board for recovery or landing deceleration.
- Stringent space vehicle requirements have accelerated the evolution of parachute technologies:
  - high reliability systems
  - supersonic parachutes
  - ultra high density packs
  - large ringsail and ribbon parachute clusters
  - simultaneity in multiple stage, large scale disreefing
  - textiles to withstand hostile or extra-terrestrial environments

Space Related Applications for Parachutes

- earth orbiting vehicle recovery: recoverable satellites
- manned spacecraft terrestrial landing: Mercury, Gemini, Apollo, Soyuz
- manned spacecraft auxiliary/emergency escape: Mercury, Gemini, Shuttle, Buran
- planetary spacecraft descent: Pioneer Venus, Viking Lander, Galileo, Cassini-Huygens, Mars Pathfinder, MER
- extra-terrestrial return spacecraft landing: Luna, Zond, Genesis, Stardust
- launch vehicle recovery: SRB recovery
- spacecraft ground deceleration: Shuttle brake parachute
- space station emergency escape: Soyuz, X38



Requirements Most Different From Terrestrial Parachutes Are For Planetary Descent

Descent System Functions

- Removal of the aeroshell from the probe
- Ensure transonic stability for the probe
- Ensure descent sequence is achieved within available timeline
- Provide a trajectory within available altitude to orientate the probe for the landing sequence (vertical) or next stage
- Stabilise the probe adequately for the landing sequence or next stage
- Achieve a velocity compatible with the landing sequence or next stage

System Sequence

- Changing ballistic coefficient (m/C_DS)
  - Single parachute (MER, Pathfinder)
  - Sequence of parachutes (Pioneer Venus, Galileo, Huygens and proposed for ExoMars)
  - Reefing
- Trajectory compatibility with requirement
- Load compatibility with system

System Sequence

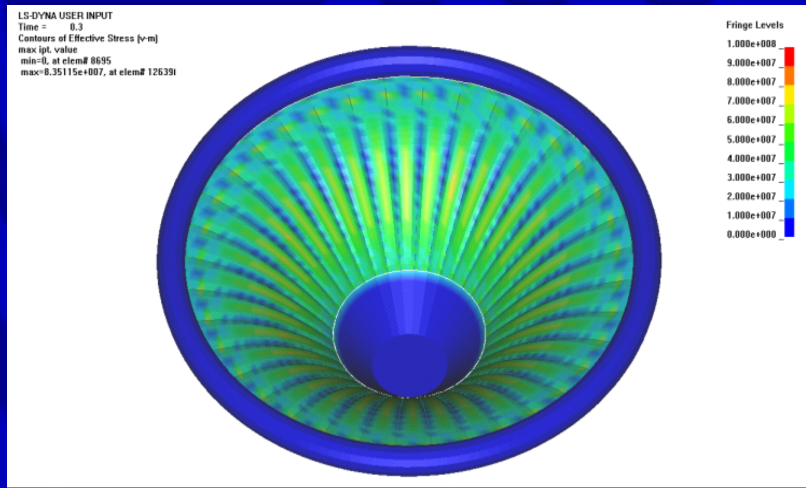
- Reefing (staging the inflation) of the parachute
  - allows load management and mass reduction
  - only used to date on Russian probes
  - can also improve trajectory over a single unreefed parachute
    - if reefed parachute is larger than single
    - at the expense of reliability
- Sequence of parachutes
  - allows load management, mass reduction and improved trajectory over a single unreefed parachute at the expense of complexity

System Sequence

- Mars is particularly challenging for high landing sites and high ballistic coefficient probes
  - Two stage system gives improved trajectory, lower loads and reduced mass
  - Higher Mach number parachute deployment is desirable but problematic because of parachute inflation instabilities above Mach 2.1.

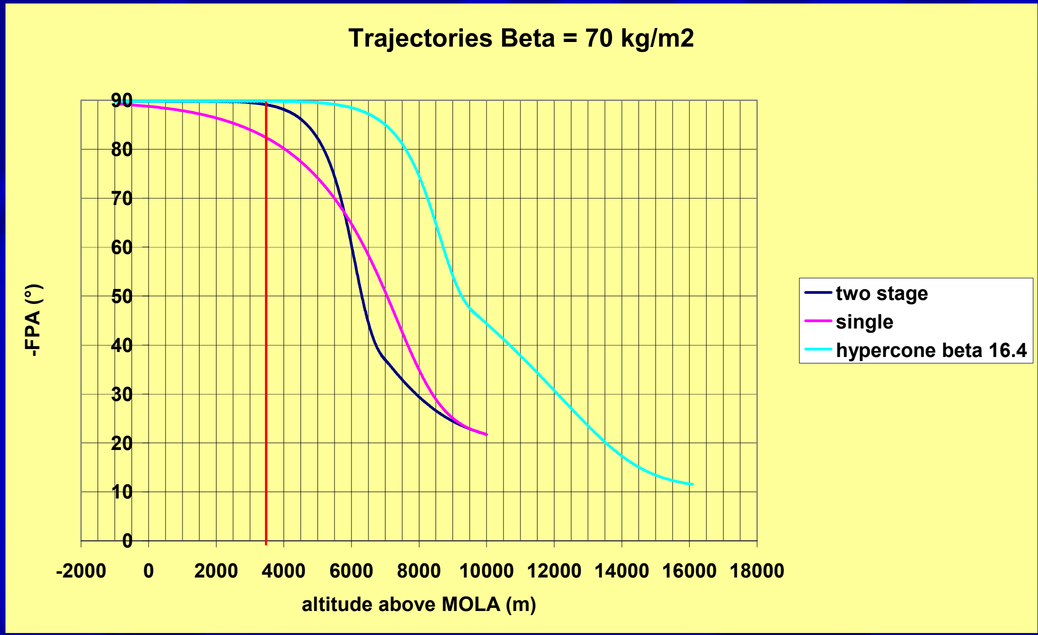
First Stage Deceleration - Inflatables

- Hypercone inflatable aerodynamic decelerator
  - provides deceleration and stabilization
  - Mach 4.0 to subsonic conditions
  - comprises an inflated torus supporting a conical fabric forward section
  - fully flexible - can be packed like a parachute
  - deployed directly - attached to the lander
- Allows reduced ballistic coefficient earlier in trajectory
- Provides effective deceleration where parachutes not feasible or performance is poor



Trajectory Performance

- 2000 kg probe
- Deployment of supersonic parachute at M = 2.1
- Deployment of Hypercone at M = 4.0
- Subsonic deployment (two-stage system) at Mach 0.8



	Two Stage	Single Stage	Two stage hcone
First stage - Type	DGB	DGB	Hypercone
First stage diameter	15.6 m	24.4m	10m
First stage mass	26.6 kg	68.0 kg	55.1kg
First stage deployment mortar	12.0 kg	30.6 kg	-
Second stage Type	Ringsail	-	Ringsail
Second stage size	31.3m D0	-	31.3m D0
Second stage mass	44.0 kg	-	44.0 kg
Total Mass	82.6 kg	98.6 kg	99.1 kg

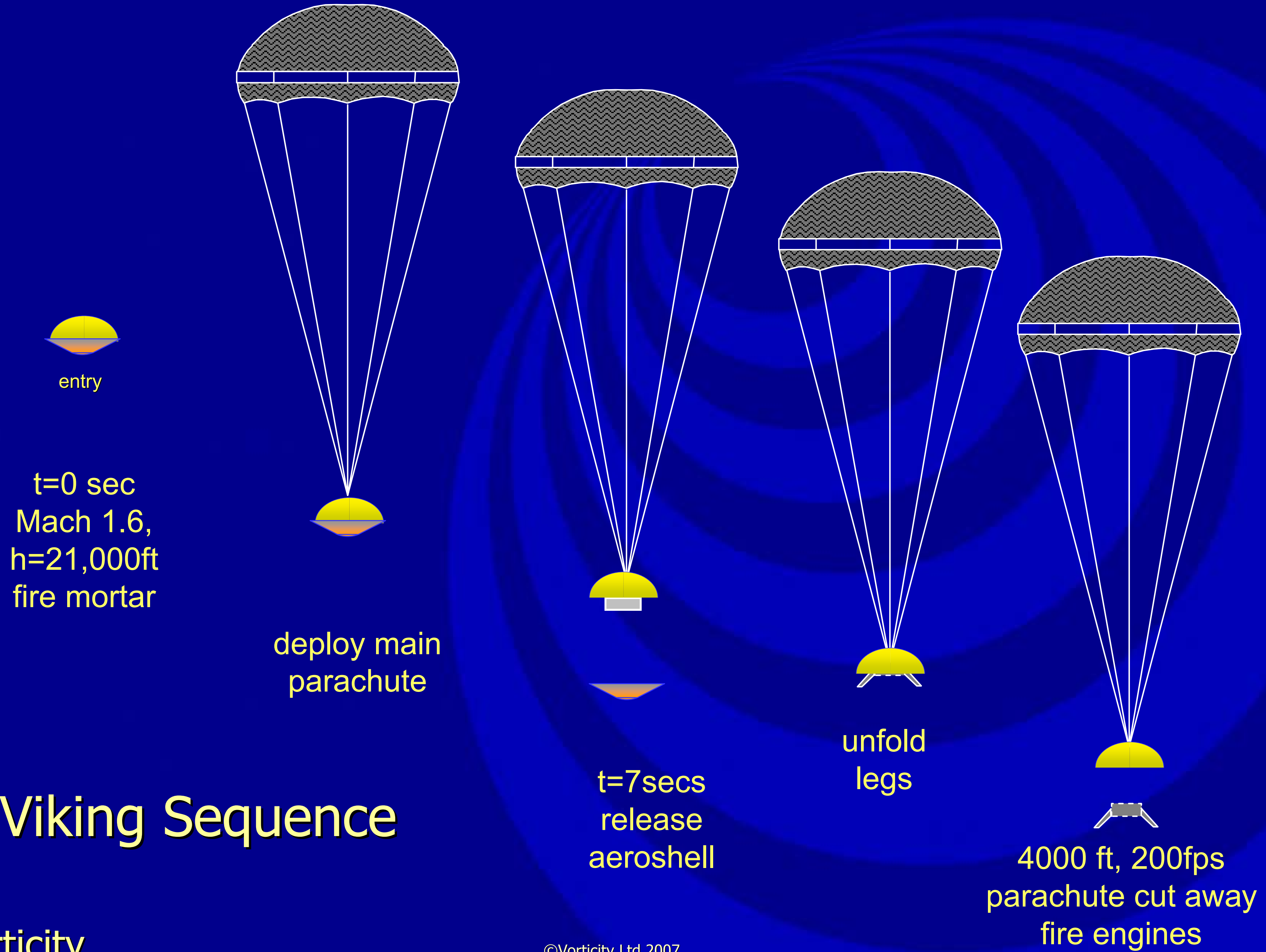
Missions

MISSION	DESTINATION	LAUNCH	ARRIVAL
VIKING	MARS	August / September 1975	July / September 1976
PIONEER VENUS	VENUS	August 1978	December 1978
GALILEO	JUPITER	October 1989	December 1995
MARS PATHFINDER	MARS	December 1996	July 1997
MER	MARS	June / July 2003	January 2004
CASSINI / HUYGENS	SATURN /TITAN	October 1997	January 2005

Descent Systems

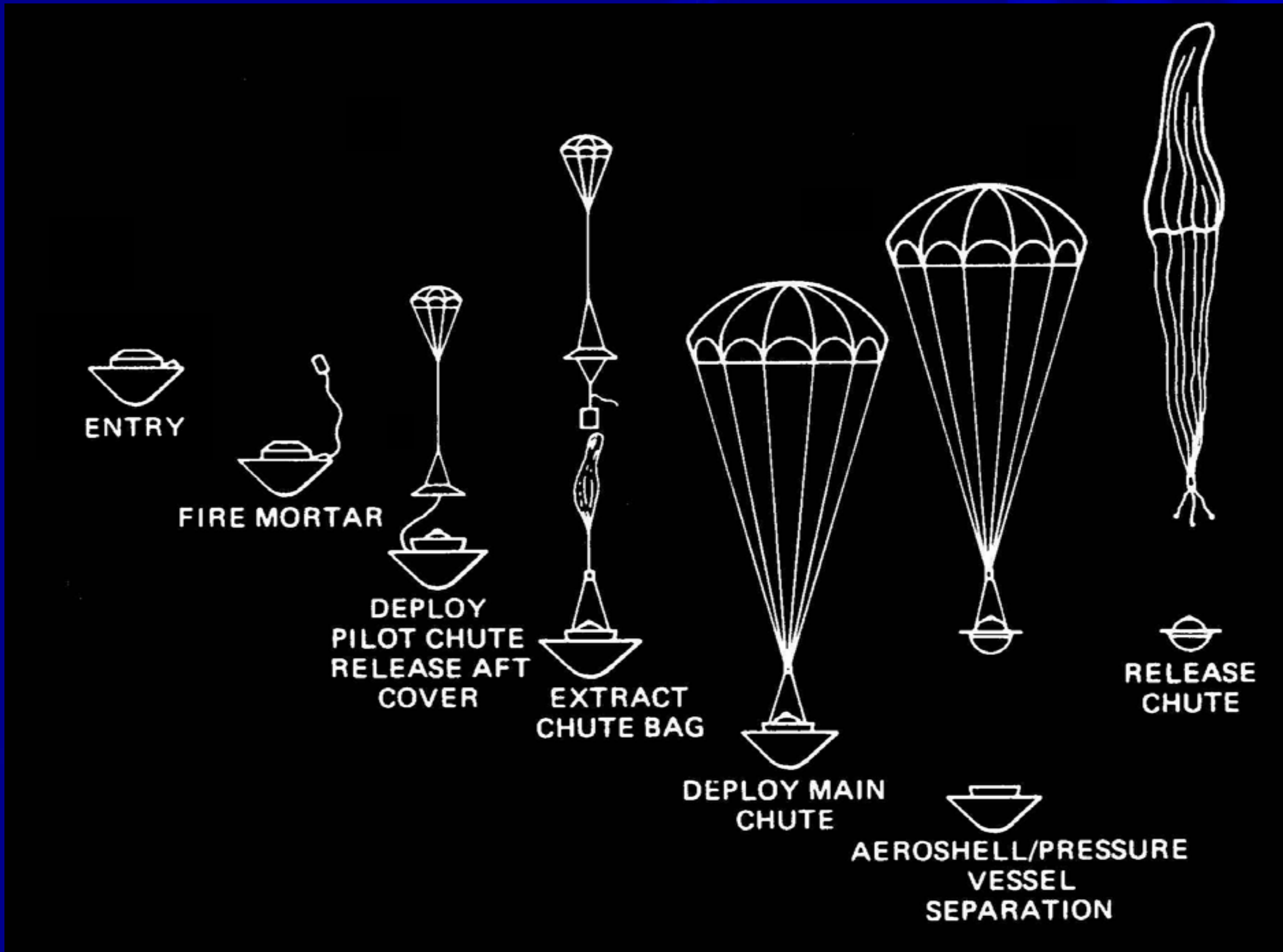
MISSION	PILOT CHUTE	MAIN CHUTE	DEPLOYMENT CONDITIONS h (km)	M	q (Pa)
Viking	None	16.2m (53 ft) Do disk-gap-band (unreefed) - mortar deployed	6.4	1.6 nominal	200 - 500
Pioneer Venus	0.76m (2.5ft) Do mortar deployed	4.94m (16.2ft) Do conical ribbon	67.1	0.8	3300
Galileo	1.14m (3.74ft) conical ribbon mortar deployed	3.8m (12.48ft) Do conical ribbon		pilot: 0.91-1.01 main: 0.87-0.97	4875 - 7648
Mars Pathfinder	None	12.7m (41.8 ft) Do disk-gap-band mortar deployed	7.5 – 12.1	1.70- 2.30	580 - 703
Cassini - Huygens	2.59m (8.5ft) Do disk-gap-band mortar deployed	8.3m (27.2ft) Do disk-gap-band	141-180	1.38 -1.73	287 - 440
MER	None	14.1m (46.3 ft) Do disk-gap-band		1.4 9- 2.30	569 - 830

Viking Sequence

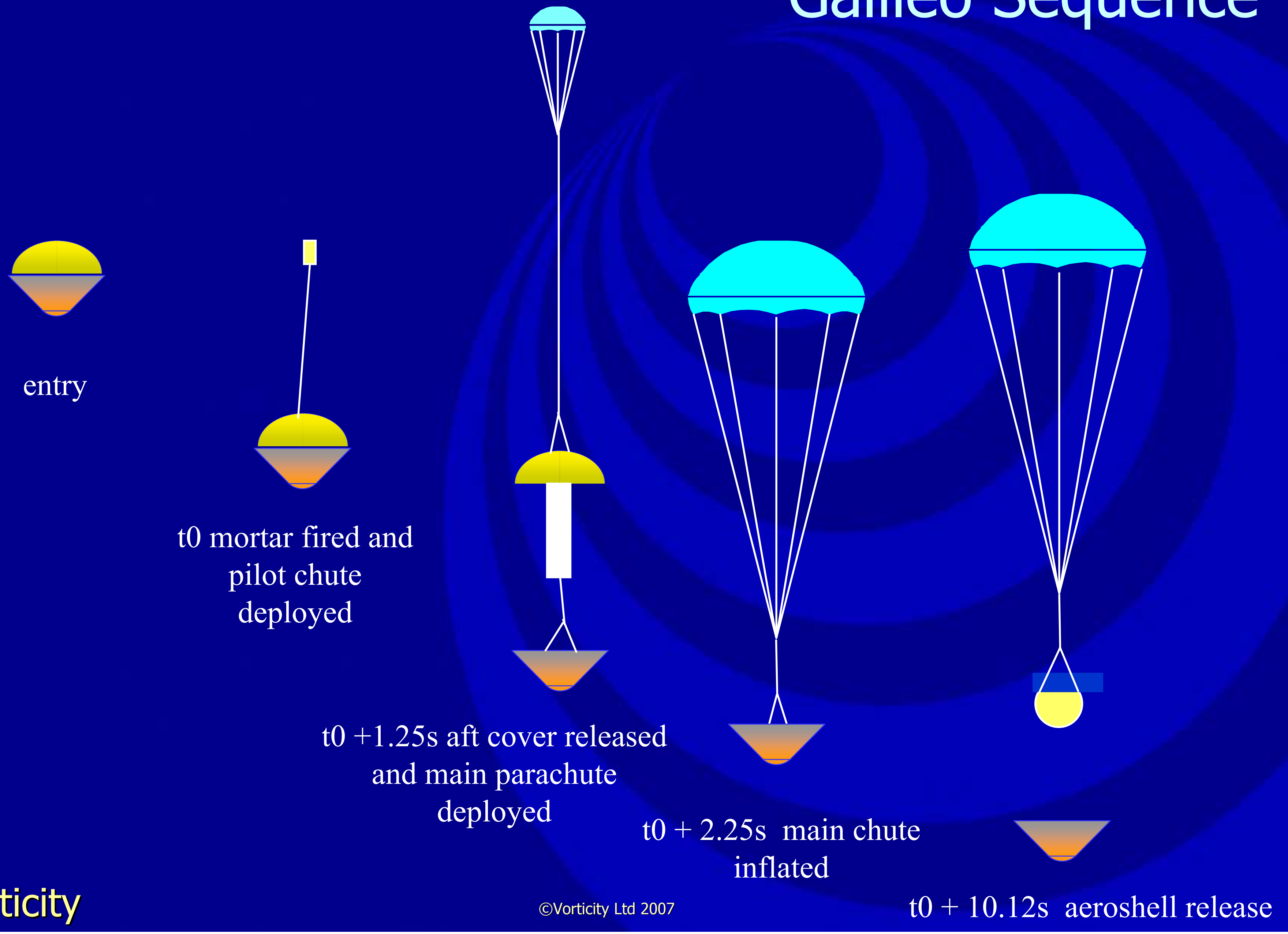


Vorticity

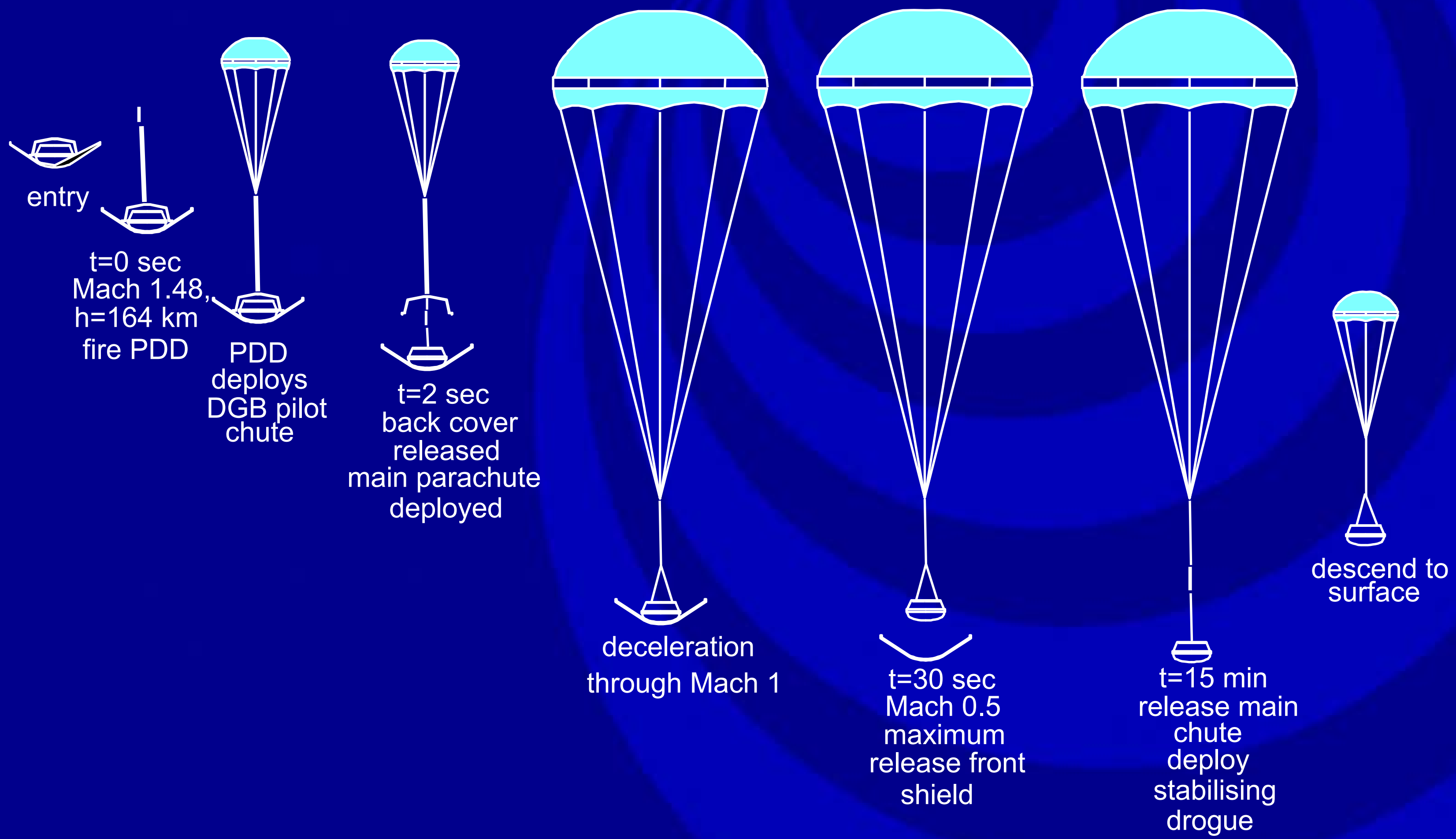
Pioneer Venus sequence



Galileo Sequence

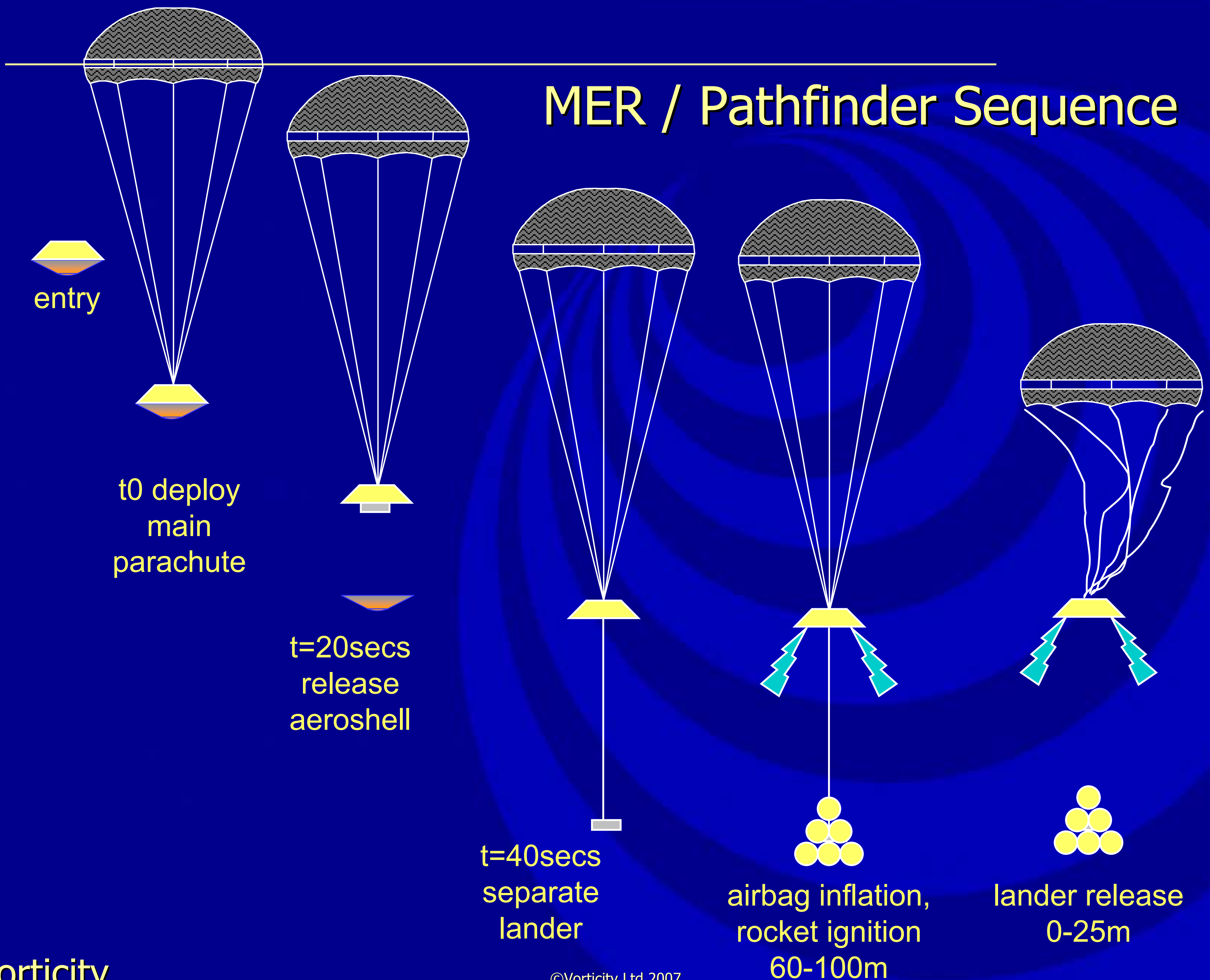


Huygens Sequence



Vorticity

MER / Pathfinder Sequence



Vorticity

Ballistic Ratio

- Separation of the various stages:
  - back cover removal
  - aeroshell separation
- is governed by the relative ballistic ratio β of the separating components:

$$\beta = \frac{m}{C_D S}$$

- the higher the ballistic ratio the lower the deceleration.
- to avoid recontacts:
  - items ejected rearward should have ballistic coefficients lower than the remaining probe
  - objects ejected forwards should have higher ballistic coefficients than the remaining probe.
- A good rule of thumb is to set the ratio of ballistic coefficients between separating objects at 0.7.

Sequence simulation and optimisation

- Earth: GRAM
- Mars: EMCD v4.1, MarsGRAM 2005
- Venus: VenusGRAM
- Titan: TitanGRAM, Yelle, Lelouche-Hunten

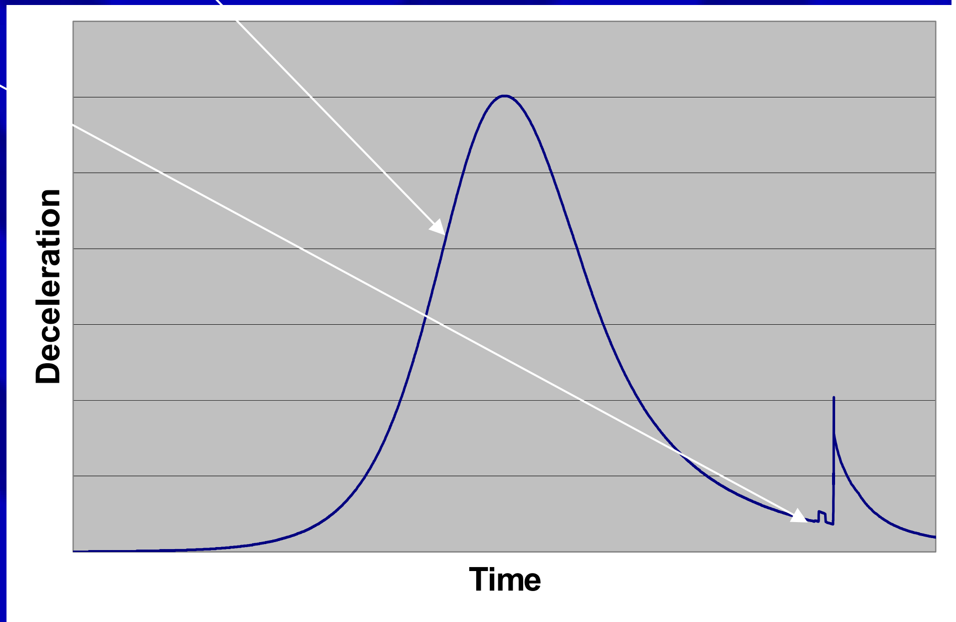
- Essential to run Monte Carlo simulations with range of atmospheric and system parameters
  - From atmospheric interface
    - State vector + covariance matrix
  - M / q map at parachute deployment
- For descent stability simulation wind modelling really needed as input to engineering wind turbulence / shear models

Descent Sequence Initiation (1)

- Objective
  - Start sequence at correct Mach number
    - Too high – Excessive loads
    - Too low – Possible instability
- Sensors
  - Mach ✗
    - Cannot measure directly
  - Dynamic Pressure ✗
    - Needs pitot tube ahead of ablator to measure
  - Acceleration ✓
    - Related to dynamic pressure
    - Simple to measure

Descent Sequence Initiation (2)

- Two stage acceleration algorithm
  - Stage 1 – Entry Detection
    - Acceleration greater than deployment accel
    - Less than minimum expected peak
  - Stage 2 - Deployment
    - Acceleration lower than threshold



Descent Sequence Initiation (3)

- Redundancy
  - Critical mission event
  - At least full redundancy
    - Huygens used 3 timers for probe activation + two independent chains
  - Mechanical backup advised
    - 'g' switch
    - Set to operate after nominal activation

Descent System

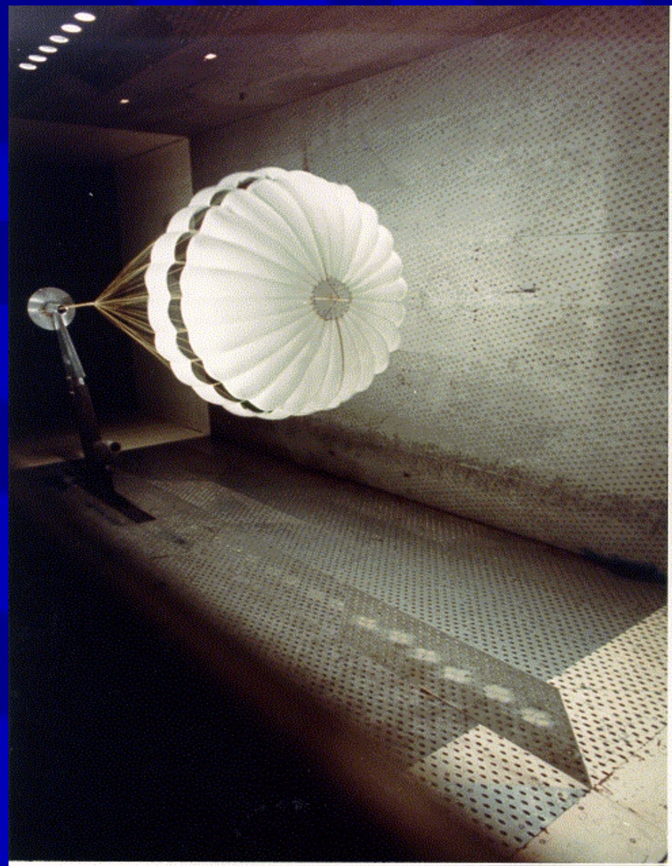
- Descent system comprises:
  - Parachutes
  - Deployment systems
    - Mortars
  - Sequencing systems
    - Release mechanisms
    - Cutters
  - Decoupling systems
    - Swivels
  - Container

Parachutes

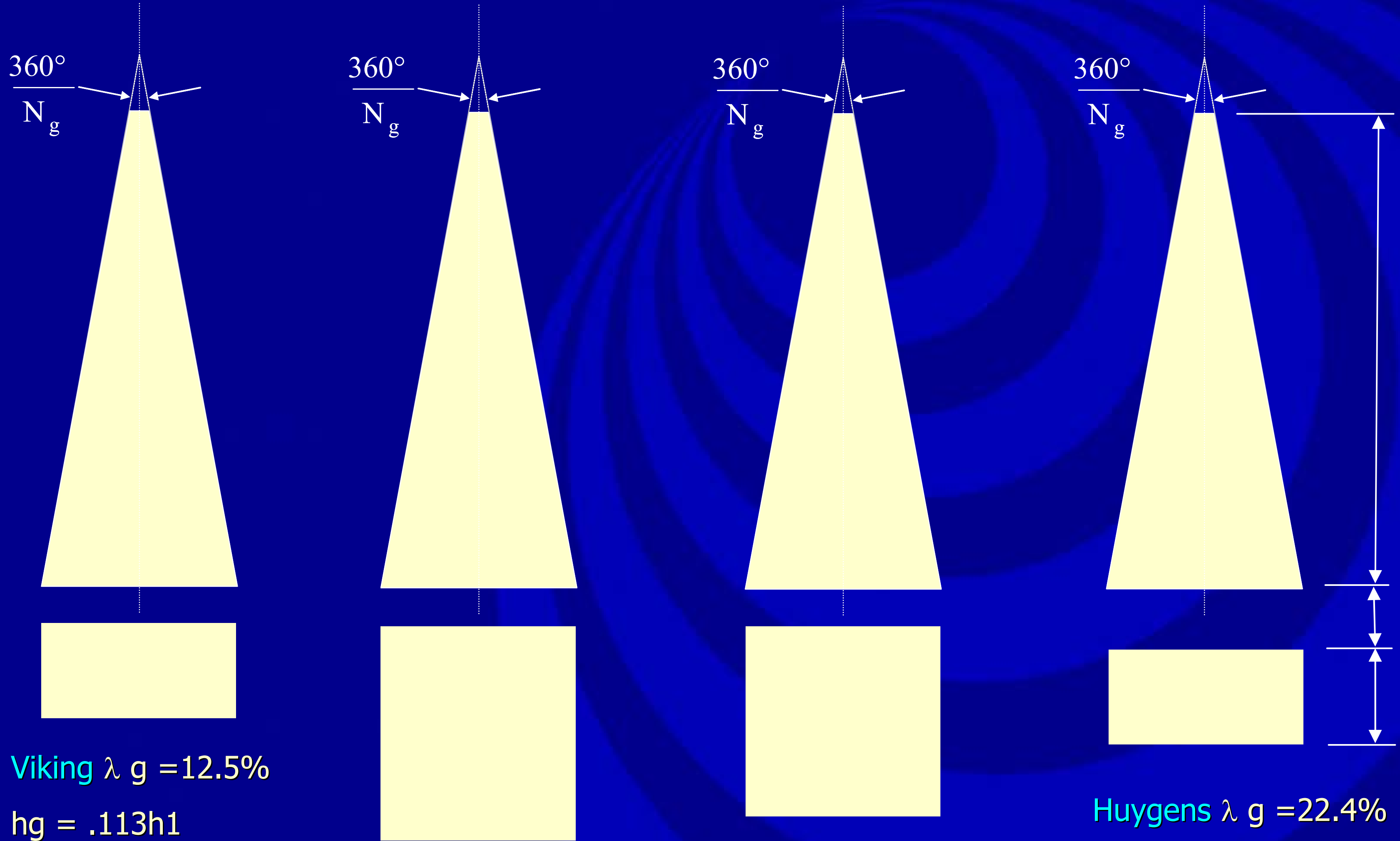
- For planetary missions parachutes require:
  - Predictable inflation performance in subsonic-low supersonic regime
  - Good drag efficiency and predictable drag performance in subsonic-low supersonic regime
  - Good stability - imaging sensors on the payloads need very high stability. Huygens requires <±10° attitude and <6°/s rate. For Pioneer Venus <±3° was required
  - Proven performance in rare combinations of M and q. For Huygens nominal deployment Mach number is 1.5 with a dynamic pressure of only 342 Pa (7 psf)
  - **Parachutes have been disk-gap-band or 20° conical ribbon**

Parachutes - DGB

- tested to Mach 2.7 but limited to Mach 2.1 operation due to inflation instabilities at higher Mach numbers
- good inflation at low dynamic pressure
- good stability (<±5°)
- lower mass than conical ribbon
- ease of wind tunnel verification



Flavours of DGB



Viking λ g =12.5%
hg = .113h1
hb = .333h1

Pathfinder λ g =8.8%
hg = .115h1
hb = .75h1

MER λ g =9.8%
hg = .122h1
hb = .677h1

Huygens λ g =22.4%
hg = .225h1
hb = .330h1

Parachutes - Conical Ribbon

- verified inflation and drag performance over range of Mach numbers (0.05 - 2.0)
- good performance at higher dynamic pressures
- good structural integrity
- good stability (<±5°)

Issues for parachutes in low density planetary atmospheres

- Supersonic performance – limited to Mach 2.1 deployment
- Porosity reduction in low density atmospheres
- Dynamic stability and manoeuvring

Supersonic Flow

- Parachutes are adversely affected by supersonic flow
  - Drag coefficient reduces with increasing Mach number above 1.0
  - Unsteady pulsing phenomenon observed
  - Limits useful Mach number range of parachutes for low q to around Mach 2.1

Supersonic Flow

- Parachute drag loss in the supersonic regime results from forebody wake interference with the parachute bow shock
- Two mechanisms for cyclical inflation and collapse have been identified
  - Parachute too close to the base of the probe allowing coupling of the subsonic region of the wake with the subsonic region in the parachute with consequential pressure bleed – criterion of $x_T > 6D_B + D_0$ proposed to avoid this
  - Other mechanism has onset between Mach 2.0 and Mach 2.4 No pressure coupling. Large bow shock movements observed resulting in large pressure fluctuations in the parachute with consequential gross shape changes

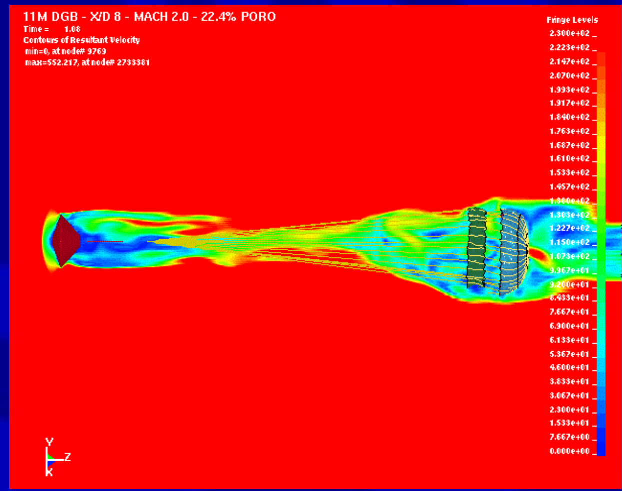
Aerodynamics

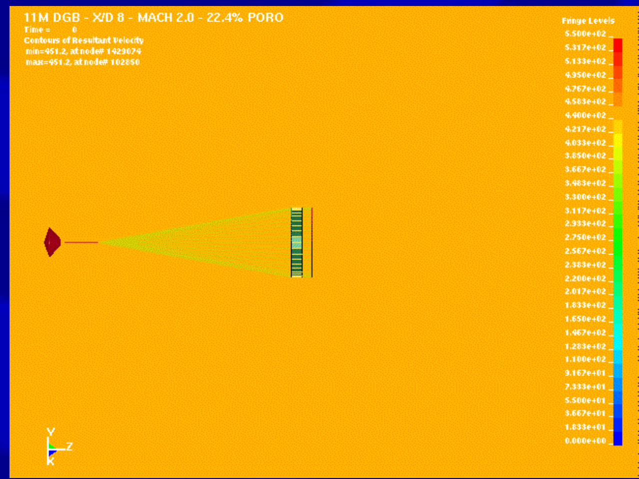
- To predict parachute performance a good knowledge of the atmosphere is necessary to calculate dynamic pressure, Mach number and Reynolds number
  - For the Viking mission the atmospheric properties of Mars were not well known resulting in the parachute being designed to operate over the Mach number range from low subsonic to Mach 2.1 and for a dynamic pressure range of 24 to 500 Pa.
  - For Huygens and Galileo the atmospheres are better defined but still quite wide margins are necessary.

Pressure coupling

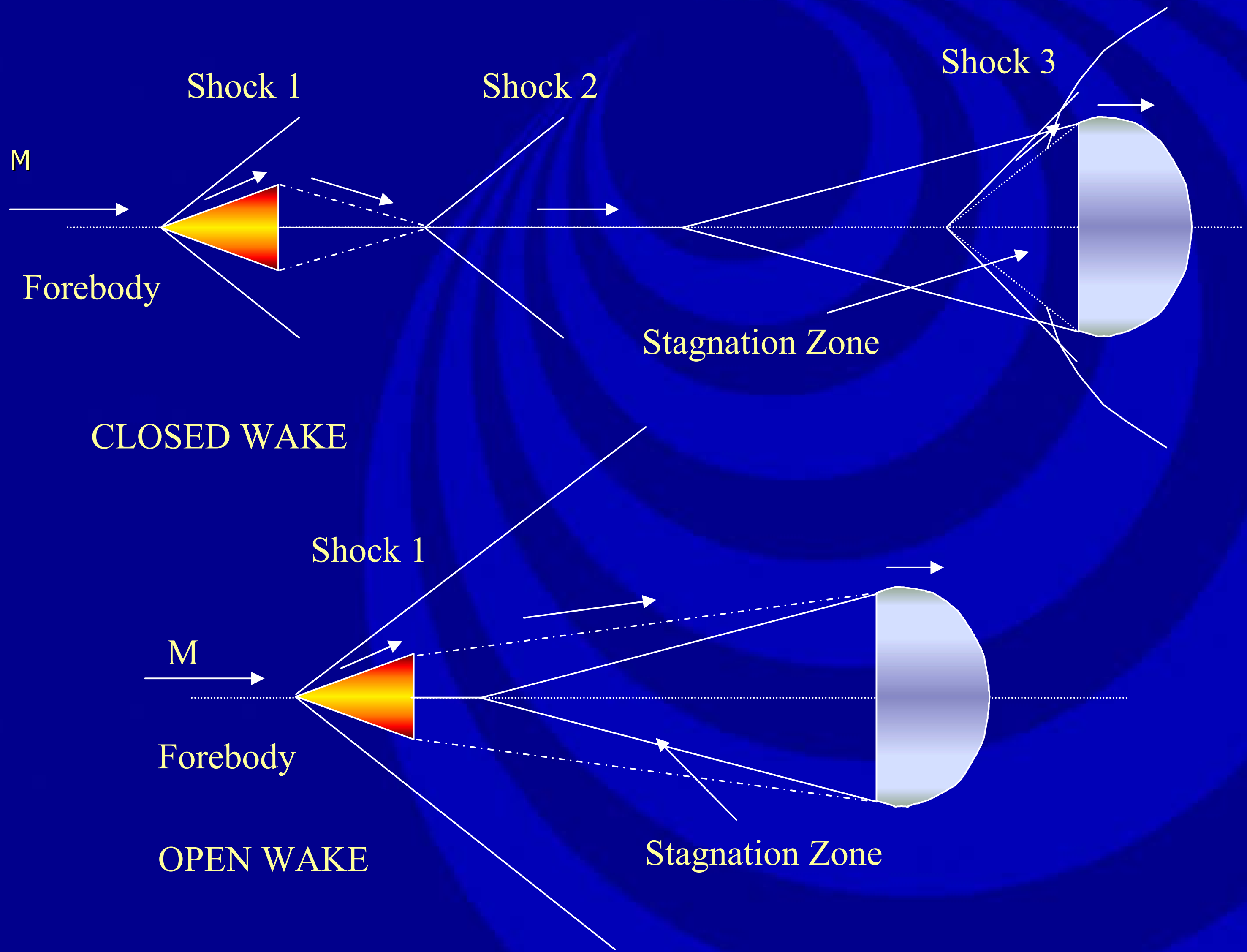
Pressure coupling occurs for:

- subsonic filaments in wake link with the stagnation region in the parachute resulting in pressure bleed forward, parachute collapse, and low drag (0.3)
- phenomenon is cyclical and results in parachute inflation and collapse increasing the risk of structural failure and reducing drag
- minimum distance the parachute should fly behind the payload should be greater than the sum of the downstream extent of subsonic filaments plus the maximum upstream extent of the bow shock
- Heritage metrics have only involved the probe size (10 D_B)
- Recent analysis suggests trailing distance should exceed $6D_B + D_0$.

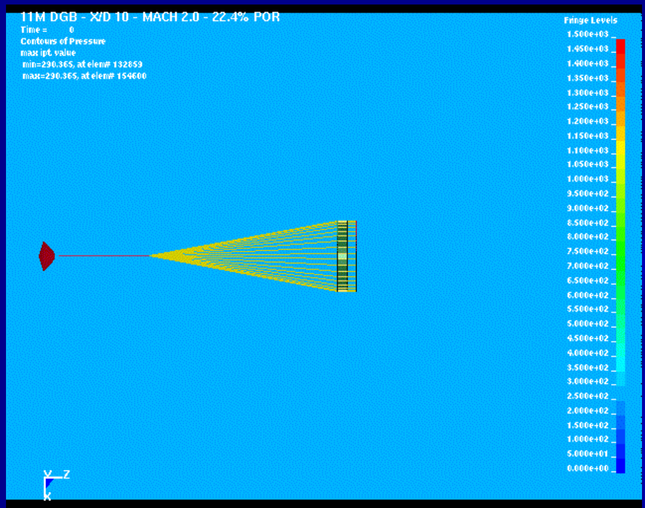


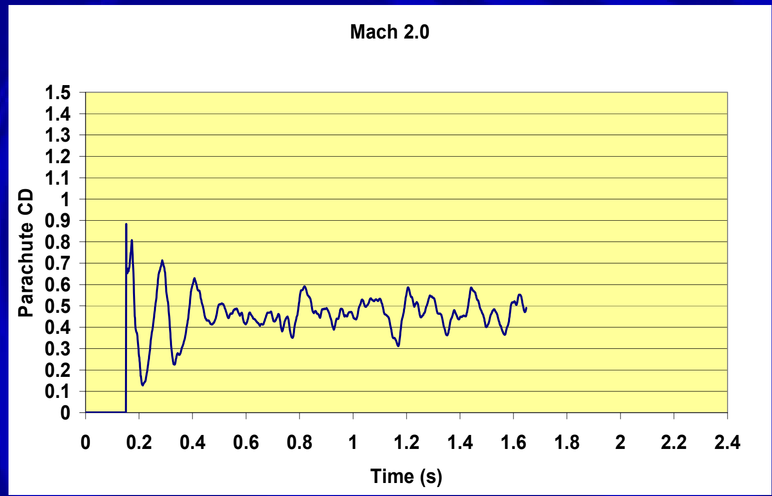


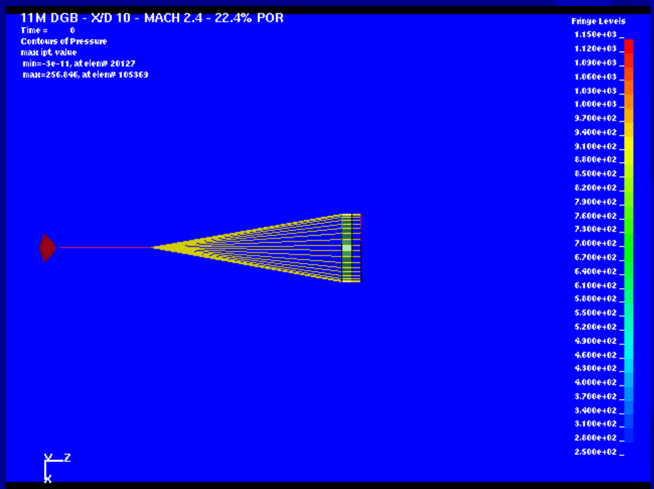
Wake effects

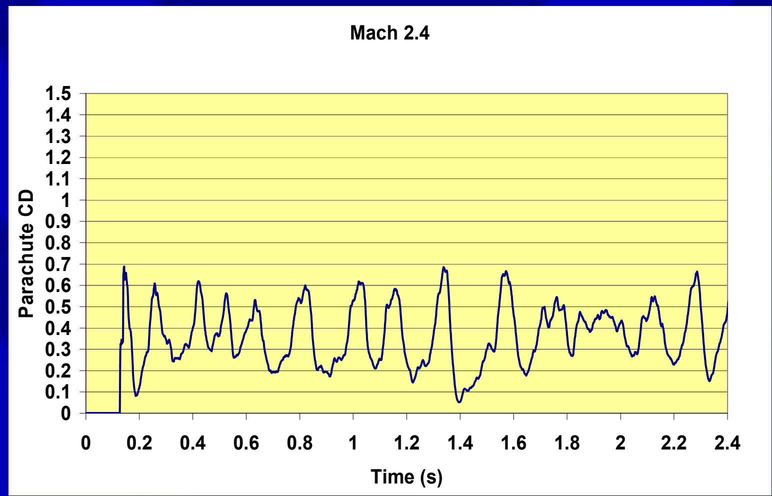


Parachute shock dynamics









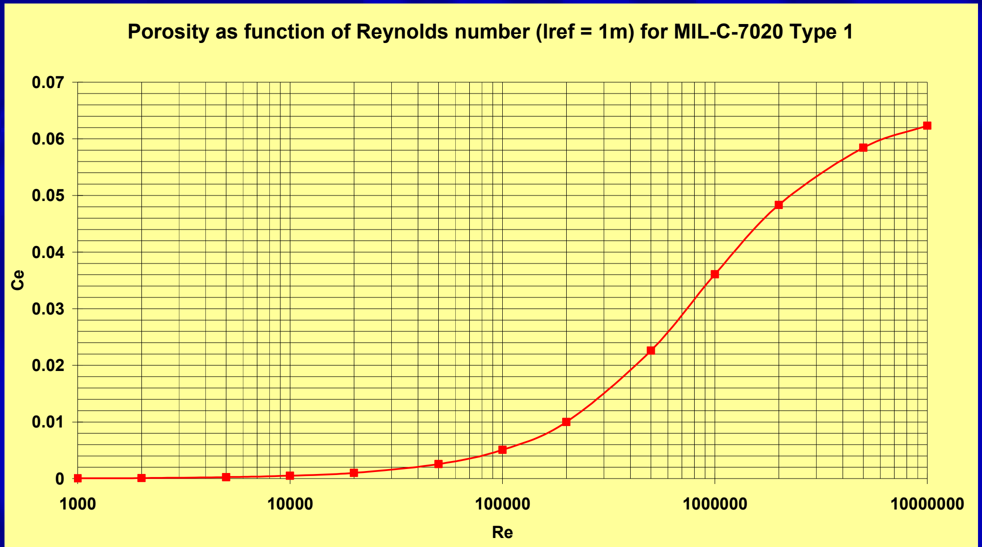
Vorticity

Trailing distance (x_T)

- Parachutes are deployed in the wake of the bluff aeroshell at transonic velocities and therefore wake performance is critical
- In supersonic flow large trailing distance for pilot and main chutes is essential to prevent pressure coupling and to give a good wake efficiency:
  - Huygens 10 D_B – no pressure coupling
  - Galileo 11 D_B (initial value of 5.6 D_B) – pressure coupling at 5.6 D_B
  - Viking 8.5 D_B – probable pressure coupling
- In subsonic flow the parachute can fly closer to the probe ($7D_B$) – wake losses can be well predicted and mass optimised

Porosity

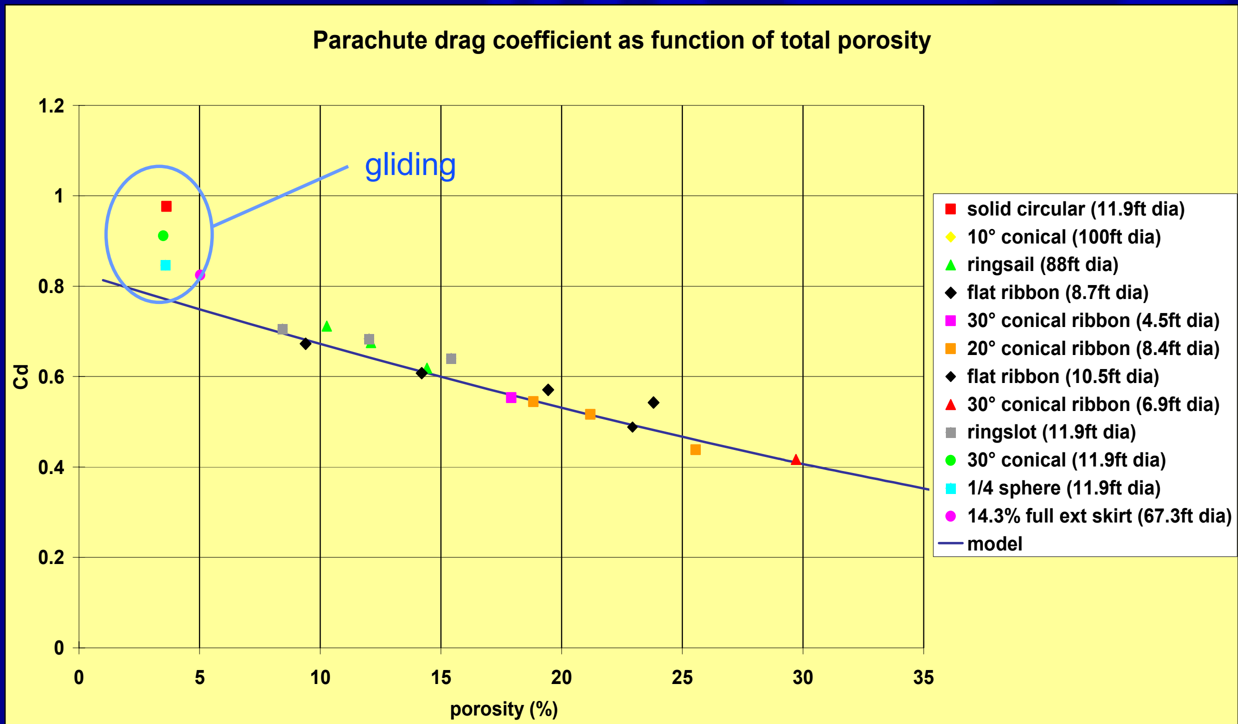
- Low density atmospheres (Mars and upper Titan)
  - Operational Reynolds number usually significantly different on Mars / Titan than on Earth
  - Drop test at low Earth altitude Re >10^6
    - Mars operation (MER) Re = $5x10^4$
    - Titan (Huygens)150km Re =$3.5x10^4$
  - Reynolds number affects cloth porosity and gap discharge coefficient
    - Increased drag coefficient
    - Increased inflation loads
    - Reduced stability



- Fabric porosity virtually nil on Mars therefore should use zero porosity material for design
- Low altitude testing poor performance indicator
- Matching only approached for high altitude testing >30km

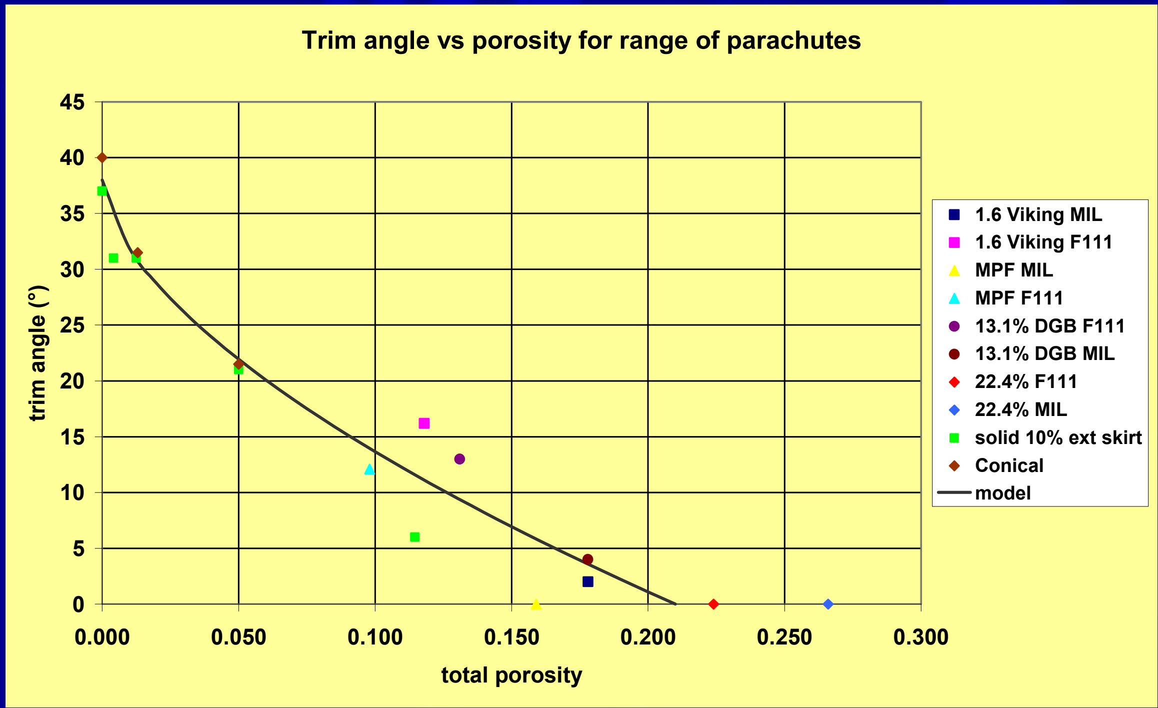
Porosity

- Drag Coefficient $C_d = f($ Mach number, porosity, line length, design$)$
  - primarily porosity
- Maximum Cd ≈0.8 - low porosity points above 0.8 are gliding



Porosity

- Trim angle is a strong function of porosity
  - parachutes with non-zero trim angle will glide, oscillate of cone depending on mass ratio $m/\rho D_0^3$
  - high mass ratio (low density) – oscillation, low mass ratio (high density) - glide



Vorticity

Flight Dynamics

- Added mass strongly affect flight dynamics
  - the mass of gas associated with the canopy – strictly the kinetic energy of the disturbance flow field divided by $\frac{1}{2}V^2$
- For round parachutes with non-zero trim angle
  - With a low mass ratio the payload is small compared to the mass of fluid associated with the canopy and the centre of mass of the system is near the canopy in these circumstances the system glides at the trim angle to the vertical
  - When the mass ratio is high the system centre of mass is close to the payload and the system oscillates or cones
- For gliding parachutes (parafoil)
  - With a high mass ratio the parachute response to control inputs very rapid and possibly uncontrollable

Flight Dynamics

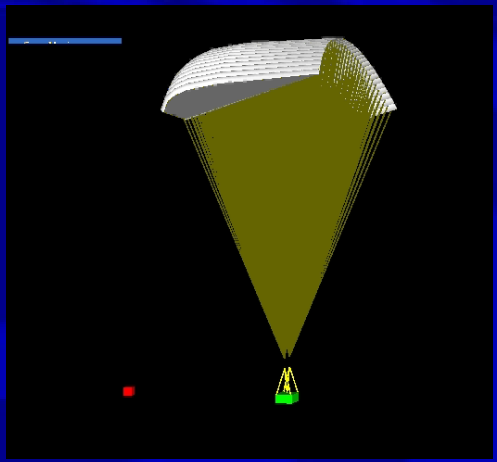
- Added mass strongly affect flight dynamics
  - the mass of gas associated with the canopy – strictly the kinetic energy of the disturbance flow field divided by $\frac{1}{2}V^2$
- For round parachutes with non-zero trim angle
  - With a low mass ratio the payload is small compared to the mass of fluid associated with the canopy and the centre of mass of the system is near the canopy in these circumstances the system glides at the trim angle to the vertical
  - When the mass ratio is high the system centre of mass is close to the payload and the system oscillates or cones

Do (m)	Earth (kg)	Mars (kg)
1	0.22	0.00
3	5.82	0.04
10	215.39	1.58
30	5815.63	42.73

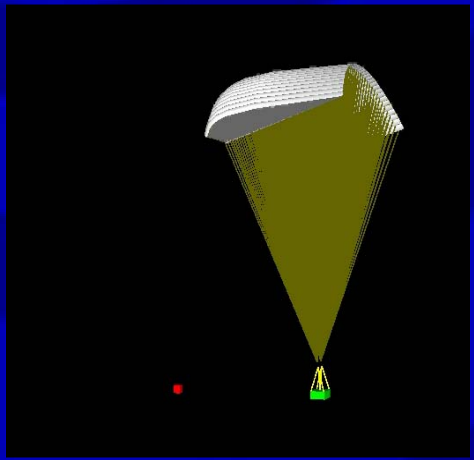
- at low altitude terrestrial density added mass is large
- on Mars it is insignificant

Flight dynamics

- Flight dynamics
  - Governed by parameter mass ratio $M_R = M_S / \rho S^{1.5}$
    - Essentially ratio of suspended mass to added mass
  - For X-38 and most terrestrial systems $M_R = 0.5 – 0.8$
  - For Mars $M_R = 13.5$
    - Canopy surge during deployment, inflation and brake release
    - High sensitivity to control inputs



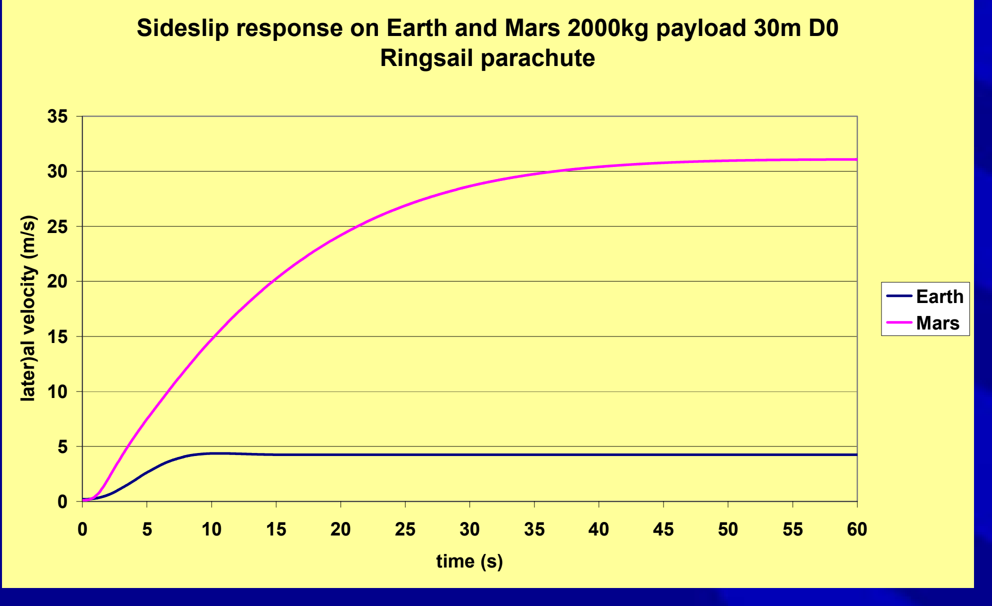
Brake release Earth

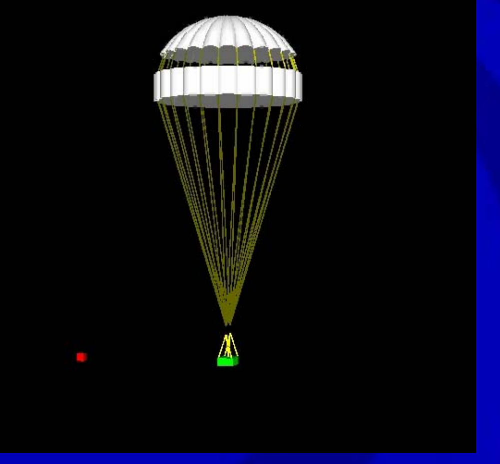


Brake release Mars

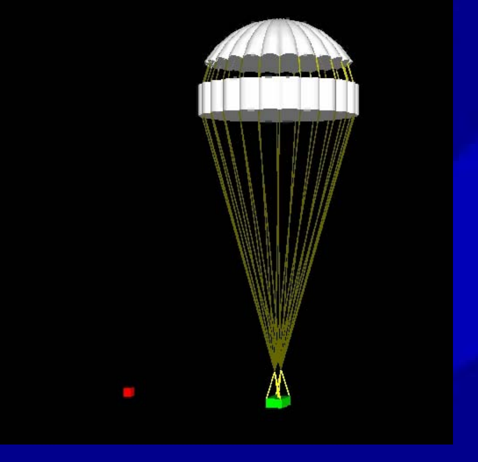
Control Options – Riser Induced Sideslip

- Control Response
  - 2000 kg payload
  - 30 m diameter ringsail parachute





Earth response

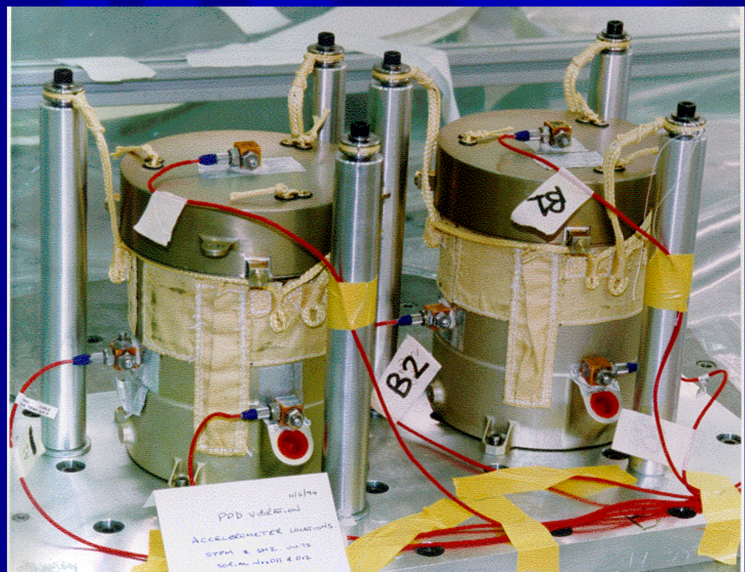


Deployment

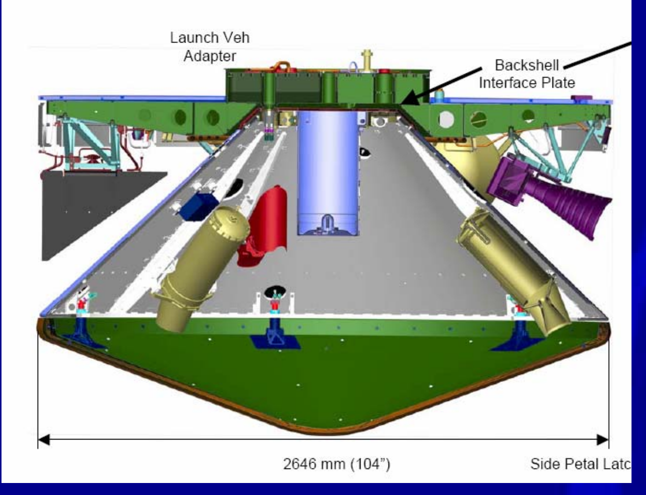
- All probes have used mortars to deploy the first stage parachute.
  - At deployment it is necessary to punch through the base reverse flow region and retain sufficient velocity for positive bag strip.
  - Deployment modelling is essential. On Huygens it was found desirable to retain the break out patch to improve deployment.
  - Deployment velocities to date have all been around 30m/s
- Alternative is to use pyrotechnic pushers to eject the break out patch and use this as a first stage drag device to extract parachute

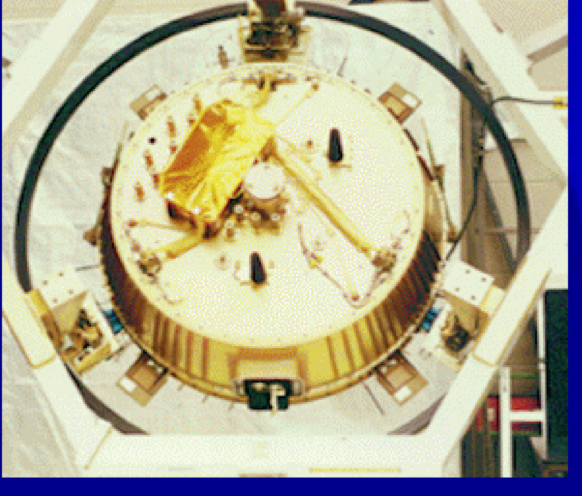
Mechanisms

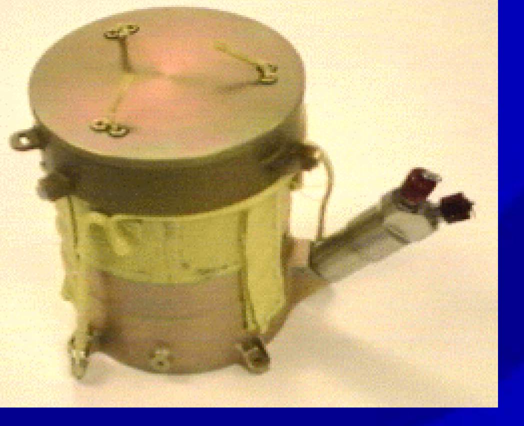
- Mechanisms for space parachute systems must be designed:
  - to meet the stringent environmental requirements
  - to have large functional margins
  - to have very high reliability



Integration







Deployments during descent

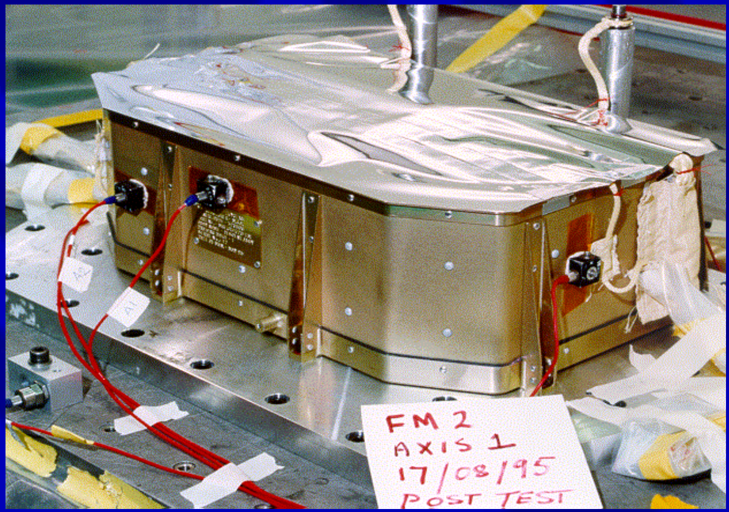
- Aerobot / Aircraft
- Things to consider
  - Velocity compatible with deployment
  - Wake effects from forebody
    - Balloons tend to be fragile
  - Deployment time
    - Must deploy before reaching surface
    - Fast deployment could damage hardware
    - Drives descent velocity and parachute sizes
  - Recontact with parachute system
    - Especially for balloons

Environments

- launch vibration
- hard vacuum
- thermal environment
  - cruise temperature
  - aero-kinetic heating
- ionising radiation
- extra-terrestrial atmosphere
- cleanliness
- ageing

Launch Vibration

- Significant vibrations, accelerations and severe acoustic input.
- Levels are specified in launch vehicle handbooks
  - Qualification levels for subsystems, which will be more severe to account for amplifications.
  - For Huygens subsystems (Titan Centaur launch vehicle) qualification sine vibration is 21g at 5-100Hz.
- Parachute mechanisms and stowage needs to be designed and qualified to the appropriate levels.

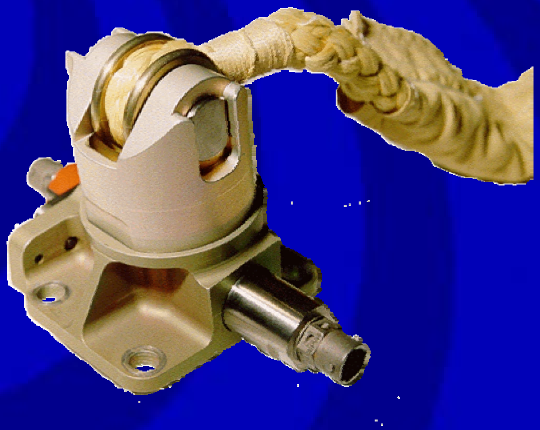


Hard Vacuum

- Many materials are affected by hard vacuum
- Some parachute materials are hygroscopic and absorb considerable amounts of water from the air (3%). This water is released once the spacecraft is in vacuum
- Specifications are set for outgassing: generally, TML (total mass loss) < 1% and CVCM (collected volatile condensate) < 0.1%.
- Many textiles, if not specially processed, generally fail these criteria - finishes and weaving aids, size, all outgas in vacuum and must be removed by scouring and bakeout. Water vapour still causes textiles to fail the TML requirement but this is usually the subject of a waiver.

Thermal Environment - Cruise

- Thermal control is one of the design drivers of space vehicles
- Environment controlled by active and passive means - for recent probes where the parachute system is internal to the probe conditions are quite benign typically +30°C to -40°C.
- There may be a requirement to contribute to the thermal balance by surface treatment of containers with photo-thermal finishes or blankets.
- Ensure the cruise/coast temperature range is compatible with mechanisms - particularly pyrotechnics.



Thermal Environment - Aero-kinetic Heating

- During re-entry, aerokinetic heating is severe. Probes use an aeroshell - back cover combination to protect the experimental module
- Radiative heating from the hot back cover can necessitate specific design measures for the parachute subsystem to avoid local temperature problems
  - Titanium fittings
  - Kevlar
  - Thermal blankets
- On Pioneer Venus the mortar and the bridle from the pilot chute to the back cover were exterior to the probe and had to be protected from re-entry heating with specific thermal insulation (RTV).
- To date parachutes for probes have all been deployed at Mach numbers below those at which direct aero-kinetic heating of the parachute is problem

Ionising Radiation

- Viking radiation specification (1 year mission) :2.7x10^3 rads
- Huygens (7 year mission) is 10^4 rads
- Galileo (6 year mission) is 2x10^5 rads, increased by Jupiter's strong radiation belts.
- For parachute systems radiation problems may arise due to total dose.
- Damage threshold:
  - Dacron >10^6 rads
  - Kevlar unaffected at 5x10^6 rads
  - Nylon 66 is resistant to 10^6 rads.

Extra-terrestrial Atmospheres

- The major problems of extra-terrestrial atmospheres are related to temperature and chemistry
- Venus atmosphere
  - 100 times denser than Earth's and considerably hotter, with surface temperatures of 500°C (932 °F)
  - contains sulphuric acid
  - Pioneer Venus parachute was designed for a maximum temperature of 80°C (it is cut away at 155,000ft) and Dacron was selected over nylon for its greater acid resistance
  - Russian Venera probe took advantage of the sulphuric acid problem and used a nylon reefing line designed to dissolve
  - gravity is 0.9 Earth gravity.

Extra-terrestrial Atmospheres

- Mars atmosphere
  - density 1/100th that on Earth and was poorly known at the time of the Viking mission
  - gravity is 0.37 Earth gravity
  - wind blown dust
- Titan atmosphere
  - cryogenic: investigation of textile materials at cryogenic temperatures and careful mechanism design for the swivel which must operate at these temperatures
  - surface atmospheric density is 5 times Earth surface density
  - gravity is only 0.13 Earth gravity

Cleanliness

- Dust and molecular contamination can jeopardise function of sensitive experiments on probes
- A particle of dust illuminated by the Sun can look like a star to a star sensor. Dust can also cause wear in delicate mechanisms
- Molecular contamination will outgas and can damage experiments
  - A mirror on Pioneer Venus was coated in parachute size during qualification
- Components must be selected not to outgas and cleaned / baked out to prevent molecular contamination
- Dust is reduced by using clean room conditions

Planetary Protection

- For missions to destinations with the possibility of extant or past life, or where there is a risk of contamination, planetary protection provisions are required (COSPAR Planetary Protection Policy)
  - Most stringent are sample return missions to Earth from Mars
- First implemented on Viking – remains "model"
- All items to be incorporated in the DLS must be compatible with microbial reduction (partial sterilization)
- Dry heating is preferred method for parachutes
  - +125°C at the minimum temperature location within the parachute system for five (5) hours
  - Waiver may be needed for parachutes processed in mortar container due to presence of water in the parachute material

Flight Duration - Ageing

- Space missions are typically of long duration:
  - lifing
- Textile materials
  - strength loss is observed in earth conditions.
    - UV
    - oxygen
  - polymers do not degrade unless exposed to a reagent or radiation
  - in space there are no such reagents and therefore most strength loss will take place prior to launch

Flight Duration - Ageing

- Viking experiments showed that the strength of Dacron, stored for six months in vacuum showed no loss over and above that attributed to thermal processing
- Vacuum will affect textile material strength by loss of water. This seems to reduce lubrication between fibres and consequently strength
- Pyrotechnic components are also lifed. Hard vacuum degrades propellant and it is essential to seal devices to a high standard. Clearly the longer the mission the better the seal necessary. For Huygens the requirement was $<10^{-8}$ cm^3/s of Helium.

Textile Materials

- Heritage
  - Polyester (Dacron) was originally selected for Viking in order to minimise outgassing and shrinkage and for its ability to withstand the material processing requirements for the biologically clean lander.
  - It was retained for Pioneer Venus because of its ability to withstand the sulphuric acid in the atmosphere.
  - Dacron was also used for the Galileo and Mars Pathfinder parachute canopies.
  - Good space heritage is therefore established

Textile Materials

- Heritage cont.d
  - Kevlar was also qualified for Viking and was used on Galileo for lines and risers.
  - Kevlar was extensively used on Huygens for lines, risers and reinforcement to reduce mass.
  - Polyester was originally selected for the Huygens parachute canopies but material of adequate quality could not be woven from the very light yarn and thus Nylon 66 was used.
  - Expanded PTFE could be an attractive material for bags, stowage loops and buffers. It is used as the external layer of the EVA suit.
  - PBO introduced on MER

Textile Materials

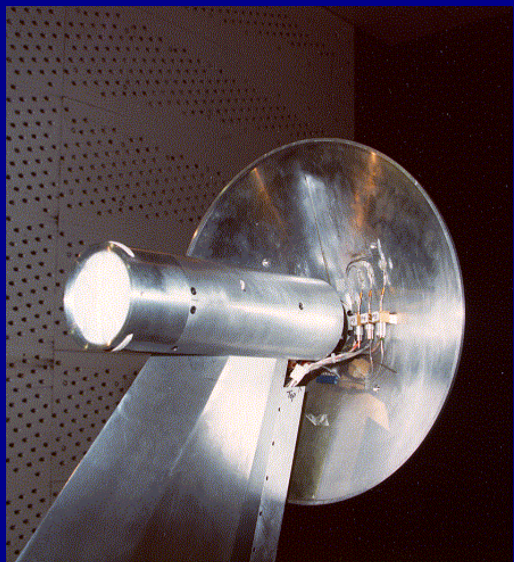
- Material Processing
  - The Viking parachutes were subjected to thermal processing to achieve the requirement for biological cleanliness (135°C for 240 hours).
  - Galileo parachutes were subjected to 132°C at 10^{-5} torr to remove contaminants.
  - Huygens parachutes are baked out at 135°C at 10^{-5} torr also to remove contaminants.
  - Dacron and Nylon materials must be heat-set to obviate dimensional changes during these treatments

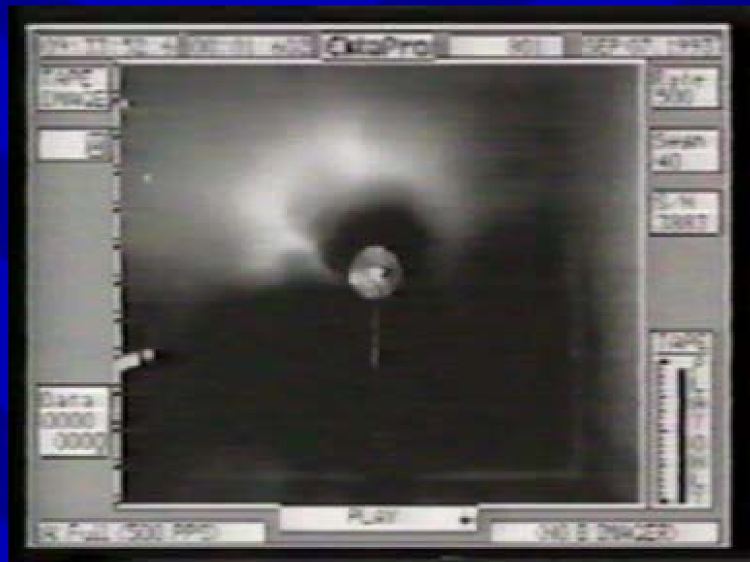
Textile Materials

- Material Processing cont.d
  - Scouring is specified as part of the material manufacturing process, to remove most finishes and size and thus to minimise thermal vacuum chamber contamination.
  - Thermal processing and the removal of size reduces strength by typically 10%.
- Material Operating Temperature
  - Low: Polyester, Nylon and Kevlar all retain good properties at -190°C (-310 °F).
  - High: Polyester 150°C (300 °F), Nylon 120°C (250 °F), Kevlar 300°C (570 °F)

Testing

- Extensive testing essential
  - Subsystem verification
    - Function following environmental exposure
    - Margins





Testing

- End-to-end testing highly desirable